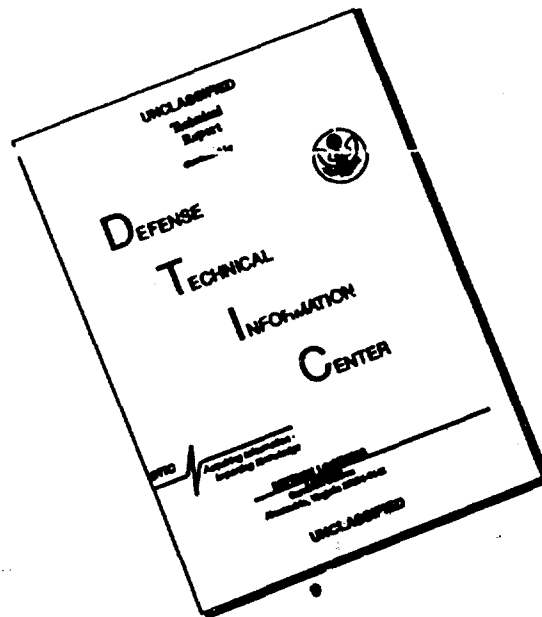


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<p>This study was conducted by the US Army Infantry Board (USAIB), Fort Benning, Georgia, to determine the most feasible approach to obtain the capability for measuring the miss distance and direction of antitank missiles fired in day, night and all weather conditions at stationary and moving targets. This study pertains to the feasibility of instrumentation design for subsonic antitank projectiles. It was directed on the basis that there is no available MDI system that provides X and Y coordinates under all conditions previously stated. As more sophisticated antitank weapons are being developed, MDI data have become critical in evaluating operational performance in a one-shot, kill-or-be-killed, tactical environment. This study was to determine the state-of-the-art of miss distance scoring in all services for all types of projectiles. By using this open approach all existing methods and their combinations were examined for possible solutions. Annexes contain discussions of the various systems which were surveyed. It was concluded that radar has demonstrated the greatest potential as a feasible approach to obtaining the required capability.</p>			

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UNITED STATES ARMY INFANTRY BOARD
Fort Benning, Georgia 31905
8 December 1971

SUBJECT: Antitank Miss Distance Indicator System

1. PROBLEM: To determine the most feasible approach to obtaining for the US Army Infantry Board (USAIB) and the US Army Armor and Engineer Board (USAAEBD) the capability for measuring the miss distance and direction of antitank missiles fired in day, night, and all weather conditions at stationary and moving targets. Target year is FY 73.

2. ASSUMPTIONS:

a. Doctrine for employment of antitank weapons will not significantly change in the near future.

b. No radical design changes are expected for antitank weapons in the near future.

c. The miss distance system required will be designed for the expanded service test environment as opposed to sterile test conditions.

d. Funds for development and procurement will remain limited.

2. FACTS BEARING ON THE PROBLEM:

a. Performance Criteria:

(1) The selected antitank miss distance systems must be capable of providing x and y coordinates of a round in space passing through the plane of the target in a real or near real time for day, night, and all weather conditions.

(2) The system must be reasonably mobile, be ready for operation in a minimum amount of time, blend into the tactical situation, and be highly reliable.

(3) Mean radial accuracy of the system should be ± 6 inches in order to provide meaningful data.

(4) The system must be capable of scoring all sizes of missiles, 66-mm and larger.

b. A system for USAIB and one for USAAEBD should not exceed \$50,000 (TECOM guidance).

c. There is no system presently available that will meet the criteria of this project.

Details of illustrations in
this document may be better
studied on microfiche

4. DISCUSSION:

a. The need for miss distance indication systems for all types of weapons has long been recognized. Dispersion patterns or coordinates of a single round contribute immeasurably to the evaluation of a weapon system. Only recently have all our efforts been taken to develop and produce suitable MDI systems. The initial phase of this study was to determine the state of the art of MDI systems and to identify potential candidates that could be modified to meet the criteria. Annexes B through I describe systems by category and their net worth to this study. (Annex A)

b. Cinetheodolites and similar optical equipment are accurate and reliable systems, and they are able to track either stationary or moving targets. Their basic principle of operation is filming with two or more instruments, measuring the miss distance information from the photographs, and solving for coordinates of the miss by triangulation. This type of system is not feasible for use under the stated conditions of this study since it cannot be used at night or in adverse weather, it does not provide real time readout of x and y coordinates, it does not blend into the tactical situation, and it is expensive. (Annex B)

c. Electrooptic devices consist of a light source and a sensor. A round breaking the beam generates a signal. By breaking two or more beams, a round can be located in space. The segmented sky screen uses skylight as a light source and is an accurate system. Furthermore, it provides real time readout and is able to blend into the tactical situation. It was eliminated as a candidate system, however, due to its inability to be used at night and in all weather, its restriction to stationary targets, the effects caused by variance of sky brightness, and cost. A similar system using a passive light for night operation was eliminated because of the complexity of the system. A third system, the automatic target scoring device, was eliminated due to its inability to blend into a tactical environment and its susceptibility to damage. (Annex C)

d. Recording observation instrument (ROI), television and photography are based essentially on the same MDI operating principle as the cinetheodolite but instrumentation is less sophisticated in nature. ROI and television provide near real time readout, while photography provides postevent data. All are presently confined to daylight operations. Television or photography should be considered as a backup system regardless of its limitations as a means of cross checking data provided by the primary MDI system. This type of approach is relatively inexpensive and it follows the adage that some data are better than none at all. (Annex D)

e. Acoustic miss distance indication is based on shock wave detection of supersonic projectiles. When rounds are subsonic, there is associated with them an irregular sound wave incapable of being electronically shaped for use with an acoustic system. Since most antitank rounds are subsonic, investigations into the acoustic concept were terminated. Seismic systems are based on detection of pressure waves through a solid medium. Since the establishment of a solid medium in a vertical plane is impractical this approach was no longer considered. (Annex E)

f. The radioactive approach to miss distance scoring is highly accurate and reliable but has several major disadvantages. It requires a cooperative round, recovery of the round, and special handling, storage, and disposal. For these reasons the nuclear approach was eliminated as a possible candidate. Laser oriented MDI has demonstrated potential and would meet all of the criteria. The state of the art is such, however, that a great deal more research and development will be required to produce a workable system. Infrared is not an MDI technique by itself but would be used in conjunction with optical devices. Although the concept is good more development is needed in this area to provide sufficient light in a tactical situation. (Annex F)

g. Cooperative rounds are probably the easiest approach to miss distance scoring. By instrumenting the missile itself many approaches can be taken to scoring. Tactical testing, however, precludes altering or modifying the test item in any manner to achieve a cooperative round. For this reason the cooperative approach was abandoned. (Annex G)

h. At present the majority of miss distance scoring is recorded by radar systems. Four basic radar principles were studied in detail, and possible modifications were considered in order to determine a solution. Continuous wave radar was eliminated since it determines velocity and not range. Frequency modulated continuous wave radar determines range but is valid against stationary targets only, due to an induced error by the doppler frequency of moving targets. This can be corrected by measuring the average beat frequency but it complicates the system considerably. Short pulse radar can be used to measure range of both stationary and moving targets but not necessarily distinguish between the two. Range-gated pulse doppler radar can be used to measure range to both stationary and moving targets and to distinguish between the two. For this reason the latter system is more desirable. (Annex H)

i. Many scoring systems in use today operate on the pulse doppler principle.

j. Although there is no system in existence configured for the purpose of this study, a mathematical analysis of two time synchronized pulse doppler systems has demonstrated to be theoretically feasible. By employing two radar systems in the plane of the target, x and y coordinates can be solved by triangulation. (Annex I)

5. CONCLUSIONS:

a. Cinetheodolites and similar sophisticated optical tracking devices cannot be modified to satisfy the criteria.

b. Electrooptic devices are not within the state of the art as an MDI system for service testing.

c. Recording observation instruments, television, and photography have potential as a system but need further development.

d. Acoustic and seismic methods are not feasible systems.

e. Nuclear and laser approaches are not suitable approaches at this time.

f. Infrared has demonstrated potential for future applications.

g. Cooperative rounds cannot be used in the service test environment.

h. Radar has demonstrated the greatest potential as a feasible approach to obtaining this capability.

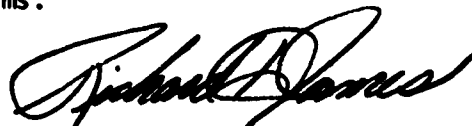
i. A mathematical analysis of a modified, range-gated, pulse-doppler radar system indicates this is a feasible solution.

6. RECOMMENDATIONS:

a. Invite industry to submit proposals for a time-synchronized, range-gated, dual pulse doppler system as an antitank miss distance system.

b. Continue to monitor state of the art with a view to developing a photographic or television capability as a limited backup MDI system.

c. Consider long-range planning for development of laser and infrared for future MDI systems.



RICHARD D. JAMES
Major, Infantry

ANNEXES

- A - General
- B - Digital and Cinetheodolites
- C - Electrooptic Devices
- D - ROI, Television, Photography
- E - Acoustic and Seismic
- F - Nuclear, Laser, and Infrared Systems
- G - Cooperative Targets
- H - Radar
- I - Mathematical Analysis
- J - Bibliography

ANNEX A

GENERAL

The need for determining the location of a round as it passes through the plane of a target has been recognized for many years in test and evaluation of weapons. In the case of small arms, fire suppression is known to be a performance degrading factor to an individual in the target area. For all caliber weapons, dispersion characteristics are vital elements in evaluating the effectiveness of a weapons system. In a tactically realistic situation the use of witness panels to collect dispersion characteristics of rounds missing the target is prohibited. The problem then arises concerning the collection of these essential data under a series of constraints. The miss distance indication (MDI) system must be able to perform in day, night, and all weather conditions for both moving and stationary targets. Additionally, the system must be accurate enough to provide meaningful data, have high reliability and low repair factors, and have real or near real time readout for an initial on-the-spot analysis of test results. The practicality of such a system is related, to a large degree, to cost. The price a testing agency is willing to pay for an MDI system is dependent upon the relative value of miss distance information with respect to other test data and the type of projectile being scored. An example of this disparity is demonstrated between the Infantry Board and the Air Defense Board. The firing of a \$250,000 missile at a \$50,000 drone requires the collection of precise, reliable data. Considering the fact that a drone is smaller than an actual target, a near miss could be considered a kill on a full-size target. MDI information in this case may constitute the most important data of the test. With the expense involved in the weapon and target and the criticality of the MDI information, high instrumentation costs may be justified in order to obtain required accuracy and reliability. The Infantry Board, on the other hand, may be willing to accept cost/effectiveness tradeoffs for its needs. Small arms ammunition is inexpensive and large amounts can be fired in a short period of time. Therefore, less sophisticated instrumentation might be employed to obtain acceptable results.

This study pertains to the feasibility of instrumentation design for subsonic antitank projectiles. It was directed on the basis that there is no available MDI system that provides x and y coordinates under all conditions previously stated. It is further justified in the fact that as more sophisticated antitank weapons are being developed, MDI data have become critical in evaluating

operational performance in a one-shot, kill-or-be-killed, tactical environment.

The first part of the study was to determine the state-of-the-art of miss distance scoring in all services for all types of projectiles. By using this open approach all existing methods and their combinations were examined for possible solutions. During this time frame many systems were logically eliminated if they could not meet the stated conditions and technological advances were not expected in the near future to overcome these shortcomings. The remaining systems were then examined for possible modifications to meet the criteria. From these remaining systems the one with the greatest potential for antitank round scoring was selected and a detailed theoretical study was conducted to determine problem areas. After identifying various concepts and potential problem areas to the most likely MDI system several manufacturers were contacted to determine the feasibility of developing the system. These discussions proved encouraging and it was determined that a solution is within the state-of-the-art.

The following annexes contain discussions of all approaches to MDI now in existence. These include a brief working concept of each system, its relationship to this project, and disposition of the system with respect to the study.

ANNEX B

DIGITAL AND CINETHEODOLITES

These are optical devices equipped with 60-inch focal length lenses and 35-mm motion picture cameras that record the image through the main objective lens, the azimuth, elevation dials, and the time at which the exposure is made. They have a dynamic accuracy of 55 ten thousandths of a degree or about 20 seconds of arc. The only difference between a digital theodolite and a cinetheodolite is that the former is a cinetheodolite with a digital printout device attached which provides real time read-out of azimuth and elevation angle. Miss distance is computed by extracting azimuth, elevation angle, and x and y coordinates for both target and missile for each exposure. With two or more cinetheodolites running synchronously standard survey methods are then used to determine the point in space of the target and projectile at each discrete time point. Normally data are extracted from three frames during the intercept portion of the flight. The computer then analyzes the data to determine the point of closest approach. One of the major disadvantages of the system is the restricted field of view. With a 60-inch focal length, miss distance measuring of large missiles is generally restricted to 50 feet or less. This, of course, must take into consideration the distance between the theodolite and missile. For air defense missiles the distances are considerably greater than for antitank missiles. Using theodolites for antitank missiles would restrict the field of view to less than ten feet radially.

A system similar to the cinetheodolite is currently in use and is known as the optical tracking mount. Its principle of operation is identical to the cinetheodolite, but it has interchangeable lenses which provide for the use of varying focal lengths. Using a 20-inch lens would provide 3 times the field of view in both azimuth and elevation that can be obtained from the 60-inch lens of the cinetheodolite. The shorter focal length, however, gives a smaller image directly proportional to the length of the lens.

In general, a combination of cinetheodolites and optical tracking mounts is used to provide full miss distance coverage. This brings about another major disadvantage of this type of system - data reduction. Results are post event and require many man-hours and sophisticated equipment. After the film from the cinetheodolite has been developed the reading process is accomplished on the equipment shown in Figure 1, Annex B. X and y

coordinates, azimuth, and elevation are extracted manually from each photograph for each optical device and hand punched into the computer bank. It takes approximately 1 minute to read one frame or exposure. These cameras operate at 30 frames per second. Assuming that 4 cinetheodolites and 3 tracking mounts are being used, as in the Vulcan service test, data are being accumulated at the rate of 210 frames per second or 12,600 frames per minute. This represents 5 man-weeks for every minute of test time or 2 1/2 man-years for every hour of test time.

Overall, these systems are very accurate and reliable, but quite expensive. The man-hours for data reduction are a large expense in itself, but two cinetheodolites (Figure 2, Annex B), the digital equipment used for synchronizing the cinetheodolites (Figure 3, Annex B), and the film reader with peripheral equipment, represents an investment of about one million dollars. Additional expense is incurred by the requirement for rapid development of large volumes of 35-mm film.

Advantages of using cinetheodolites for a miss distance indication system for antitank missiles are:

- (1) Accuracy and reliability of the system.
- (2) Ability to track either stationary or moving targets.
- (3) Pictorial representation of the near miss.

Disadvantages of the system include:

- (1) Inability to perform at night or in adverse weather conditions.
- (2) No real or near real time readout of x and y coordinates.
- (3) Difficulty of blending into the tactical situation.
- (4) Expense

Based on an evaluation of the above advantages and disadvantages, it has been determined that cinetheodolites and similar instrumentation will not serve the purpose of an MDI system of antitank weapons under the stated conditions. No developments are expected in the near future to negate the listed disadvantages.

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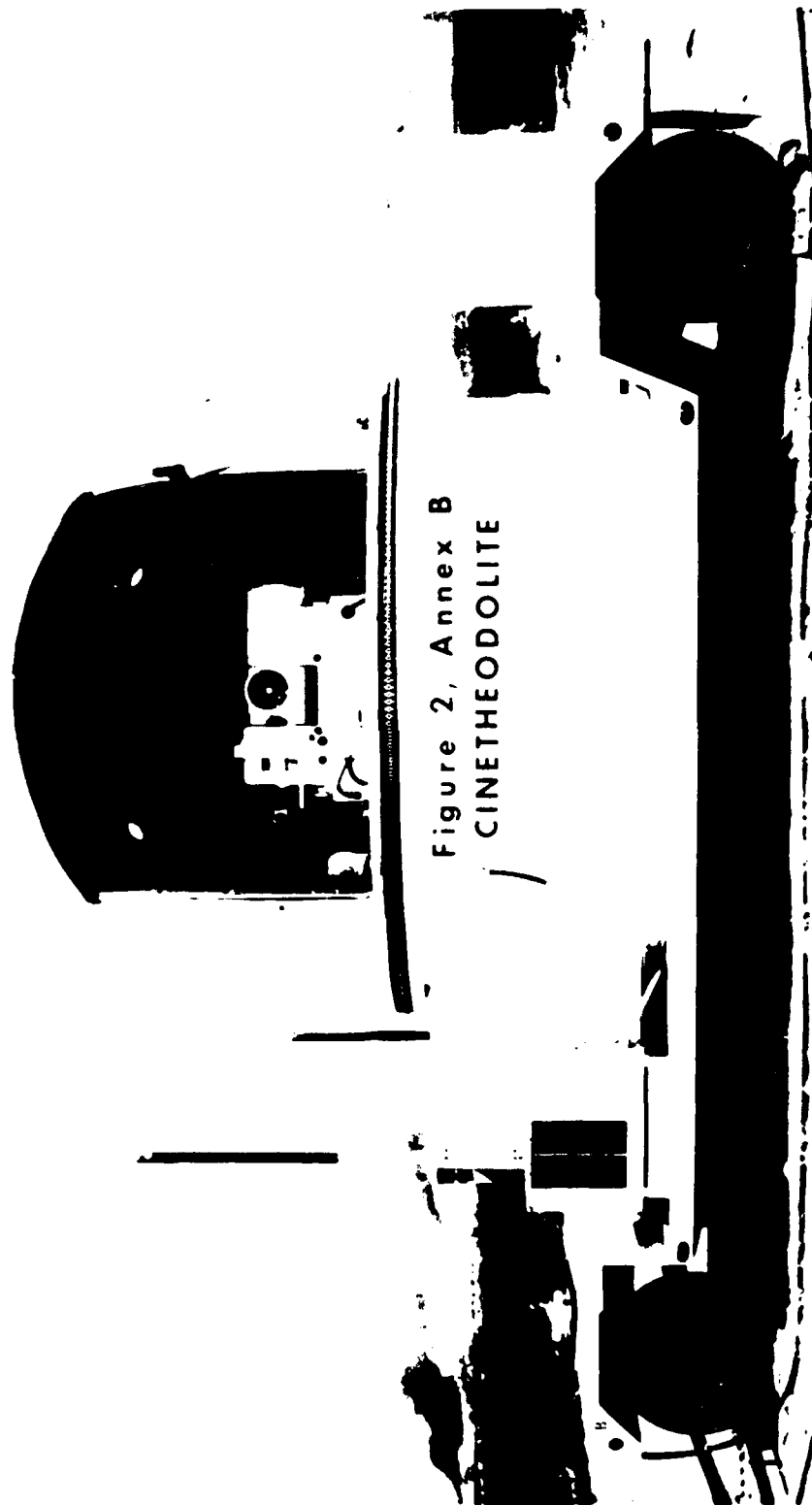
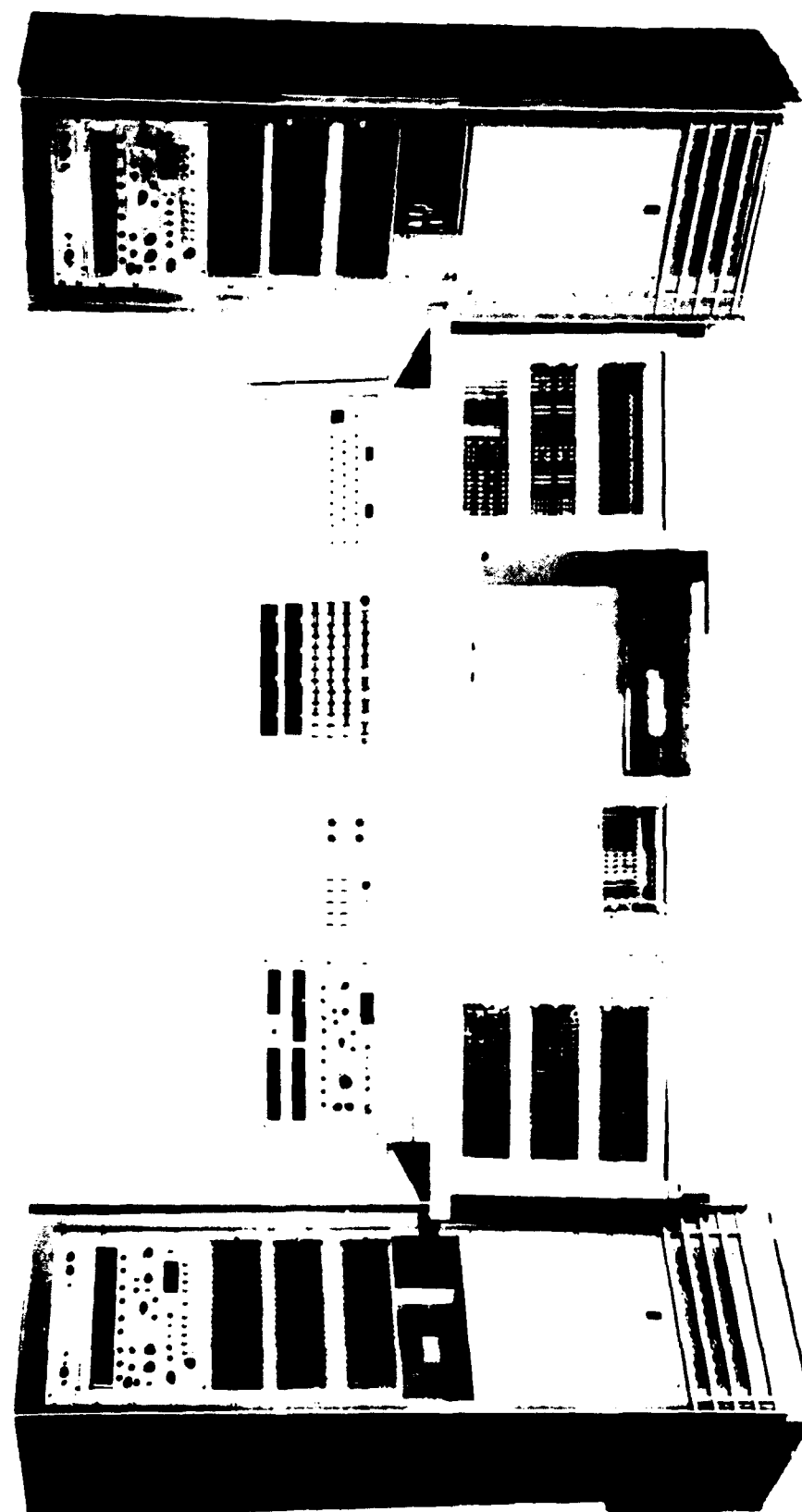


Figure 2, Annex B
CINETHEODOLITE

Figure 3, Annex B
DIGITAL SYNCHRONIZING EQUIPMENT



ANNEX C

ELECTROOPTIC DEVICES

There are several methods in existence today for accumulating miss distance information through the principle of a light source and electronic sensors. This approach demonstrated potential and was investigated in detail to determine its net worth with respect to an MDI system for subsonic antitank missiles.

The segmented sky screen is a system that has been in the test and evaluation field and found to be valuable in certain environments. A typical segmented sky screen consists of skylight as the light source, two optical detector assemblies, and a display console (Figure 1, Annex C). Each optical detector assembly consists of a column array of detectors observing segments of a fan beam of light. Each detector in an optical detector assembly subtends approximately 3 mils and would contain about 64 sensors in accordance with current usage. Two detector assemblies located in different positions, but on line with one another, create an overlapping pattern of segmented beams of light with an invisible screen effect. With 300 feet between the detector assemblies along the base line the defined target area would be approximately 35 feet across with a resolution of about 5 inches. This means accuracy would be approximately ± 2.5 inches. X and y coordinates are obtained when a projectile passes through the screen and breaks one or more beams from each sensor assembly. The overlapping beams define that point in space through which the projectile passed.

The first segmented sky screen tested made use of photomultiplier tubes as detectors. The use of solid state detectors was investigated in an attempt to reduce the size of the unit and improve ruggedness as well as to permit the use of a low voltage battery pack. Tests of solid state units demonstrated potential but more work is required to develop automatic gain control circuitry. Automatic gain control is required to eliminate electronically changes in the sky from the detector. Sky brightness may vary on a given day as much as 10 to 1 which could preclude the round from triggering the detectors since the intensity change resulting from the round is only about 5 percent.

Advantages of this system include:

- a. The ability of the system to blend into the tactical situation.
- b. Accuracy of ± 2.5 inches.

c. Ability to tailor the optical detector assemblies in order to change the dimensions of the target scoring area.

d. Real time readout.

Disadvantages of the system include:

a. Inability to perform at night or in all weather.

b. Restricted to stationary targets.

c. Insufficient development of solid state circuitry to preclude effects from variance in sky brightness.

d. Estimated cost of \$150,000 per system.

Final evaluation of the advantages and disadvantages eliminated the sky screen as a candidate for an antitank missile MDI system. Although a feasible concept is not within the state of the art at present, this may be the most promising system in future years when development of artificial light and adequate circuitry will eliminate effects of varying conditions and permit day, night, and all weather use. Once development costs have been excluded, the system will have a relatively low price tag.

Another system investigated as a possible candidate incorporated the use of artificial light, thereby permitting its use at night. The system operates on the same principle as the segmented sky screen but with a slightly different configuration. The basic system incorporates the use of a light screen at the target plane, an optical sensing device up range and off to the side, and digital readout equipment.

The only advantage of the system is its semimobility which would permit testing at any location and gives a reasonable amount of installation and calibration time.

Disadvantages of the system include:

a. Inability to be used in conjunction with moving targets.

b. Present projectile velocities are limited at the lower end to 700 feet per second which would preclude testing several antitank subsonic rounds.

c. Ranges are limited.

d. Optical view of the sensor is limited to a 4x4 foot target area.

e. A gate-on period time must be adjusted for each type of ammunition. This precludes a weapons mix test.

f. There is a requirement for perfect alignment of the sensor and the light screen. Under tactical conditions this is difficult at best.

An evaluation of the advantages and disadvantages indicates that the disadvantages strongly prevail. Although the basic principles are the same, the hardware for this system is more sophisticated and delicate than for the segmented sky screen. This system demonstrates, however, that the use of passive light is being tried, and effective instrumentation for miss distance indicating using this approach can be expected in the future.

Other instrumentation using electrooptical principles includes a very reliable and accurate device known as the automatic target scoring system. Rounds are fired through a frame which contains the electronics. One side of the frame contains a light source while the other contains a bank of detectors. As the round passes through the screen, a beam is broken and the x coordinate is provided in the form of real time readout. The same principle applies to the top and bottom of the frame where the y coordinate is provided. Without discussing the advantages and disadvantages of the system several conclusions can be drawn. It has demonstrated to be an excellent system in sterile test conditions. Its accuracy is claimed at ± 0.05 inch, and the reliability is high. The obvious drawbacks are the inability of the frame to blend into a tactical situation and its vulnerability to damage. Additionally, the target area is small and would have to be greatly increased to accommodate testing of antitank missiles.

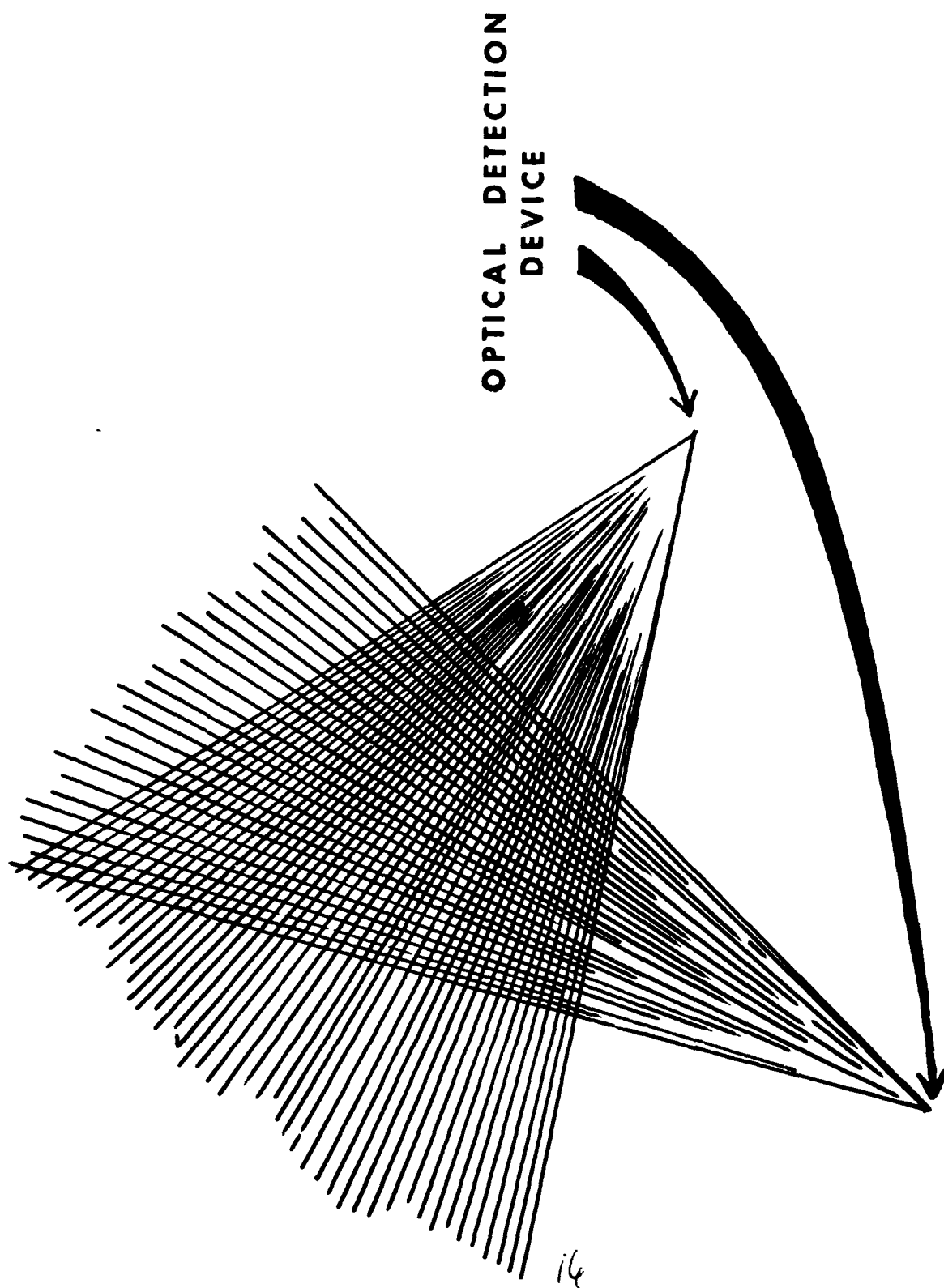


Figure 1, Annex C
SEGMENTED SKY SCREEN

ANNEX D

RECORDING OBSERVATION INSTRUMENT, TELEVISION, AND PHOTOGRAPHY

These three approaches to miss distance indication are based essentially on the same principle. It should be noted that this principle is identical to that of the theodolites discussed in Annex A, but the instrumentation contained in this annex is less sophisticated in nature and considered to be more feasible for antitank MDI.

The recording observation instrument (RDI) is an optical device by which the observer aligns a reticle sight with an object on the ground or in space. It is essentially a free moving, precision theodolite linked with a continuous nixie tube display of both azimuth and elevation angles reading to the hundredth of a degree. (Figure 1, Annex D) Finding the coordinates of a target at a discrete time point is accomplished with standard survey methods using two or more RDI's. By having surveyed positions for each RDI a line for each instrument can be determined by using the azimuth and elevation at the desired time. At present, azimuth and elevation readings are synchro-nized by voice command which could account for a great deal of error. In the case of a round passing through the plane of a target, a means would have to be devised to record data from all individual instruments at the same instant. Although accuracy is given as ± 5 meters, this is with respect to a slant range of 7000 meters or less than one percent of the distance between the instrument and the target. It is felt that accuracy could be improved with a new reticle configuration.

Some of the advantages of RDI include:

- a. Simplicity and durability.
- b. Relatively inexpensive at approximately \$16,000 a set.
- c. Near real time readout.
- d. Mobility.

Some of the disadvantages include:

- a. Not accurate enough for antitank MDI, although it could be improved with telescopic lenses and new reticle configuration.

- b. Operator error as a result of manual locking and recording by means of pushbutton.
- c. Inadequate synchronizing mechanism for two or more RDI's.
- d. Inability to function at night or in adverse weather conditions.
- e. The need for surveyed locations.

An analysis of the advantages and disadvantages demonstrates the inadequacy of RDI at the present time to meet the objectives of this study.

Television as an MDI system has been used in various configurations with success under limited environmental conditions. As with other optical devices the technique requires two or more cameras that will provide a solution to x and y coordinates by means of triangulation. One of the major differences in extracting data from television is that azimuth and elevation of each camera are generally fixed on the target area. Miss distance data is then measured linearly from the face of the screen. Simple equations can then be used to find the x and y coordinates. It is not feasible, however, that continuous monitoring of azimuth and elevation of each camera could be utilized in conjunction with the linear measurement from the monitor screen to provide near real time readout of miss distance data.

An interesting use of television for MDI is presently being done in Stockholm, Sweden. It involves the use of two TV cameras coaxially located with two radar systems. In this manner the radar system provides position data (target azimuth, elevation angle, and slant range) of the target during a firing run. It determines when the round and the target are coincident and this frame is marked on the TV recorder. Once again MDI data are extracted linearly from the face of the TV screens and calculated to determine x and y coordinates. The interesting point of the system is that a manned target is used. This is accomplished by reversing the azimuth synchro leads to one TV radar system causing it to track a mirror image space position of the real target. The gunner then fires blank ammunition at the target while a slave system fires live ammunition at the mirror image. The point illustrates a unique use of TV as an MDI system.

A suggested but undeveloped technique is to make use of the image scanning lines on the TV picture tube itself to locate a round in space. As an electron moves back and forth across a

screen producing the image of the target area, it will cross the missile at some discrete time point. It is thought that precise measurements could be electronically obtained from each monitor and standard techniques used to determine x and y coordinates.

With the development of improved infrared TV cameras for use under low light level conditions, greater potential has been demonstrated for an MDI system. Although capabilities of this system are severely limited by range from the camera to target, having cameras down range in the target area could be a feasible solution. This would not be feasible for moving targets at the present time.

The major advantages for using television as an MDI system would include:

- a. Near real time readout.
- b. Mobility.
- c. Hard copy data.
- d. Accuracy.

Some disadvantages include:

- a. No night or all weather capabilities.
- b. Equipment is sensitive to field conditions over a prolonged period of time.
- c. Two cameras with monitors and synchronizing equipment would cost approximately \$50,000.
- d. Cameras with an IR source would not be able to track moving targets.

An analysis of the advantages and disadvantages indicates that television is not quite ready to be pursued as an MDI system for this study.

Photography is one of the oldest and most effective means known for determining miss distance data. Cameras vary in price range, and equipment can be produced tailored to meet the needs and budget of the user. Since the basic principle of using two or more optical devices has been explained thus far, it will not be repeated. It should be noted that the technique in Sweden using dual television radar mirror image systems is also employed

in Bern, Switzerland, using cameras and radar. The only difference is that the latter system provides post-event data.

A new technique still under development is the one-camera system of photographic interpretation of miss distance data. It is a relatively simple system based on the laws of photogrammetry and has a proven theoretical feasibility. The method used is to track the missile through the plane of the target, determine in which frame the missile is passing through the target plane, and manually measure the x and y coordinates from the photograph by having an object in the photograph from which to scale. Determining which frame the round is in in the target plane is derived empirically. By choosing the most constant film speed and experimenting with each type round at known distances, the number of exposures per linear distance can be established. The most desirable position of the camera is on line with the weapon. If the camera is offset, however, there is a simple, mathematical formula for correcting the angle of incidence. This technique will require considerable refining before it can be used effectively as an MDI system.

The advantages of photography include:

- a. Reliability.
- b. Accuracy.
- c. Inexpensive.
- d. Mobility.

The disadvantages include:

- a. Inability to use at night or in all weather.
- b. Inability to track moving targets without more sophisticated equipment.
- c. Post Event Data

At a glance, the disadvantages are shown to relate adversely to critical criteria for an antitank MDI system.

All of the techniques listed in this annex have demonstrated inadequacy for a solution to this study, but several factors should be noted. They are reliable, have varying degrees of accuracy and cost, and are readily accessible from a manufacturer.

Photography is a proven method and probably the most reliable and most accurate. A backup system must be considered for the primary MDI system. Photography appears to be the most feasible system as backup. Its advantages are the facts that it provides a hard copy of the data, is inexpensive, and will provide sufficient data to correlate with the primary system. The fact that it will not function at night is minimal since day firings could determine the net worth of the primary system overall.



Figure 1, Annex D

R.O.I.

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ANNEX E

ACOUSTIC AND SEISMIC MDI METHODS

The concept of acoustic miss distance indication rests on the fact that as a supersonic projectile moves through the air, it creates a disturbance in the air due to its motion. This disturbance, which is actually a pressure wave, radiates in all directions from the point where it was created by the projectile. The spherical waves produced move from their point of creation at the velocity of sound. If the projectile is moving at a velocity greater than sound, it tends to leave spheres of disturbance behind itself. Pressure sensitive microphones or other transducers are then used to detect the shock wave as the round passes through the plane of the target. As the velocity of a sound decreases and reaches the subsonic state, the sphere of disturbance is no longer a shock wave but now becomes an irregularly shaped sound wave. It was thought that a means might be devised to electronically shape this irregular wave and make use of an acoustic MDI system for this study. After probing for a possible solution, it was determined that this approach is not within the state-of-the-art, and further investigation into acoustics was terminated.

The seismic approach to miss distance indication is used for impact locating rounds and is based on the principle of transmitted shock waves through a solid medium. Since it is not feasible to develop a homogeneous solid target to cover the entire scoring area, this approach was no longer considered.

ANNEX F

NUCLEAR, LASER, AND INFRARED SYSTEMS

These three systems have been grouped into a single annex simply for convenience since their principles of operation are in no way related.

Radioactive material has been successfully used in the field of miss distance indication, but is still not considered a desirable method. The basic concept in radioactive sensing is the use of a cooperative round. Cooperative rounds will be discussed in Annex G, so it will be sufficient to state here that a cooperative round is one that has been instrumented. In the case of the nuclear approach, a round is generally taped with a radioactive substance and as it passes the target a scintillating device on the target is able to detect radiation intensity. This method is extremely accurate (as accurate as the cinetheodolite), but there are several major disadvantages. Even though a radioactive substance with a short half life is used to facilitate rapid decay, the Atomic Energy Commission requires recovery of every round. This can cause numerous problems especially in the case of lost rounds. Additional requirements when using radioactive materials are special handling, storage, and disposal methods. All require special licensing and become tedious to manage. Based on the short description of nuclear MDI systems, it has been determined that this approach is not feasible for this study.

The principle behind the laser is light amplification by stimulated emission of radiation. More generally it is a device that utilizes the natural oscillations of atoms for amplifying or generating electromagnetic waves. One of the most promising uses of laser in the military service is that of range finding. The laser works in much the same manner as the radar in that it emits a pulse that bounces off the target and receives a return signal. As with radar, the time it takes for the pulse to emit and return determines range. Due to radar antenna patterns, its wave tends to spread, but the laser's intense beam is highly directional. The major disadvantage of laser is that the slightest atmospheric disturbance distorts the beam, which precludes its use under many field conditions. Until just recently laser was able to pulse only in the 10-nanosecond range which meant considerable error at short ranges for MDI. In recent times, however, laser has progressed to pulsing in the billionths of a second time frame which provides extremely accurate data.

Overall, laser is still in its infancy and will require more development for a stable, reliable MDI system. Long range planning should begin now for design and procurement of laser MDI systems.

Infrared (IR) is a technique that makes use of thermal radiation of wave lengths longer than those of visible light. The principle of infrared in itself does not constitute an MDI system, but its use in conjunction with television and photographic equipment provides a passive light source for obtaining data during periods of reduced visibility. As mentioned in Annex D, the use of IR with television has demonstrated potential; with further development, an adequate system for miss distance scoring could evolve. The problem with an IR source still remains - providing sufficient light to cover a large single target or multiple target areas. Still another factor to consider is cost. The use of infrared should be considered in long range planning for an MDI system, but for the purpose of this study its practicality is deemed non-feasible.

ANNEX G

COOPERATIVE TARGETS AND PROJECTILES

Cooperative targets incorporate all or part of a miss distance indication system within the target itself. The most predominant cooperative target presently being used is the drone aircraft instrumented with radar transmitters, receivers, and telemetry data links. A more sophisticated system is being studied at present to be used with the new high altitude supersonic target. The workings of this system are discussed in Appendix 1 of Annex H. The major advantage of a cooperative target is that it facilitates maneuverability since it is a self-contained unit. The proposed solution for an antitank MDI system could be considered a cooperative target since it places two radar systems in the plane of the target. In the strictest definition of a cooperative target, however, the MDI instrumentation is exposed and susceptible to destruction by the projectile. This is its major disadvantage. In the case of the antitank MDI system the instrumentation will be shielded by a berm for all targets and will be attached to the carrier instead of the target for all moving targets.

Cooperative projectiles are ones that have been instrumented with all or part of an MDI system to facilitate miss distance scoring. The nuclear approach mentioned in Annex F is an example of a cooperative projectile. The round itself is carrying the radiation source while the target contains the remainder of the MDI instrumentation. Another example of a cooperative round would be one that carries a transmitter of some sort while the receiver and data link are located with the target. The advantages of this system are increased accuracy and less complications concerned with synchronizing and time pulsing. The service test environment, however, prohibits altering the test item for fear of changing the ballistic characteristics of the projectile. Projectiles can be designed and manufactured to carry additional instrumentation and at the same time match the ballistic characteristics of the original round, but it is felt that the advantage gained would not justify the additional costs involved with such a design. Another disadvantage of cooperative rounds is the nearly inevitable destruction of the instrumentation in the round. Because of the two disadvantages listed above cooperative rounds were no longer considered for an antitank miss distance indication system.

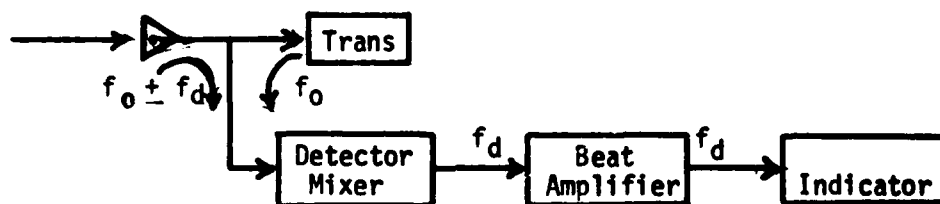
ANNEX H

RADAR

An in-depth study of radar and radar techniques was undertaken to determine its application to MDI. During this study four basic radar concepts or techniques were studied, and modifications to each were considered. The four basic radar concepts studied were continuous wave (CW) radar, frequency modulated CW radar, short pulse radar, and pulse doppler radar. Range gate modifications to pulse doppler radar techniques were also studied to determine its feasibility as an antitank MDI system.

CONTINUOUS WAVE (CW) RADAR.

The doppler effect is the basis for a continuous wave radar. Since a continuous wave radar is continuously sending out a radar signal, a means of separating or distinguishing between the transmitted signal and an echo signal is required. This means is provided by the doppler effect. The CW radar transmits a signal at a frequency f_0 which travels until it makes contact with an object. If this object is moving, the reflected signal or echo has a frequency differing from the transmitted signal by $\pm f_d$, the doppler frequency. Therefore the echo signal is of a frequency to $f_0 \pm f_d$. The received echo signal enters the radar via the antenna and is heterodyned in a detector (mixer) with a portion of the transmitter signal f_0 to produce a doppler beat note of frequency f_d as shown in the block diagram below.



By definition the doppler frequency $f_d = \frac{2v_r f_0}{c}$

Where v_r is the velocity of the target with respect to the radar and c is the speed of light. Using this relationship, it is relatively simple to determine the velocity of the target. This is the type radar used by police to detect speeders.

FREQUENCY MODULATED CW RADAR.

Simple CW radar cannot be used to determine range. The signal must be time marked in some manner if range is to be measured. This time marking permits the time of transmission and time of return to be recognized. Time marking is accomplished by frequency modulating the CW signal as shown in the diagram below.



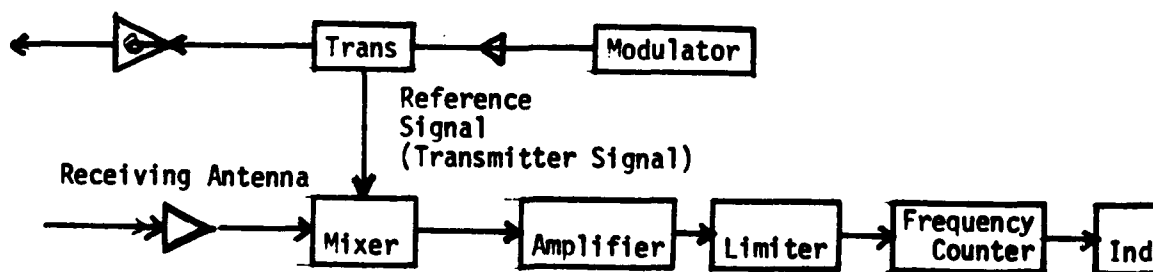
CW Wave Form



Frequency Modulated CW Wave Form

In the frequency modulated CW radar (FM-CW), the transmitter frequency is changed as a function of time in a known manner. The signal is transmitted by a transmitter and antenna and the echo is received by separate antenna and receiver. Some of the transmitted signal is fed directly to the receiver and the transmitted signal and the echo are then heterodyned to produce a beat of frequency f_b . If there is no doppler shift in the echo, i.e., the target is stationary and not moving with respect to the radar the beat frequency is a measure of the targets range and $f_b = f_r$ where f_r is the frequency due only to the targets range as shown in the block diagram below.

Transmitting Antenna



Knowing the modulating frequency, f_m , and the range of modulation, f , the beat frequency is given by the formula

$$f_r = \frac{2R}{c} 2f_m \quad \Delta f = \frac{4Rf_m}{c} \quad \Delta f$$

where R is range to the target and c is the speed of light. Thus measuring the beat frequency determines the range.

If the target is moving with respect to the radar an error will be induced in a range calculation due to the doppler frequency f_d . In this case the beat frequency f_b does not equal the frequency due only to the target's range f_r but $f_b = f_r + f_d$. This error can be corrected by measuring the average beat frequency, but it complicates the system considerably.

It is possible to modify this type radar for use with multiple targets but in many cases the practical difficulties inherent in its modification outweigh the advantages to this type system.

SHORT PULSE RADAR.

The principle behind this type radar is very simple. The transmitter sends out a short pulse radio wave and then cuts off. This short pulse travels until it strikes an object where it is reflected and the receiver then picks up the reflected signal or echo. Knowing that the radio wave travels at the speed of light and measuring the time between the time of transmission and the time of receipt the range may be determined by the formula

$$R = \frac{cT}{2}$$

where

R = range

c = speed of light

T = time of transmission t_t minus time of receipt t_r .

Because of its principle of operation, this type system is much less complex than the two previously discussed, but there are still inherent disadvantages.

A transmitted signal is much stronger than the returning echo. Therefore, while the transmitter is on the receiver cannot distinguish the echo from the transmitted signal without a mixer. This is the basic reason for a pulsing system. The transmitter is on only a brief time and then it cuts off. While the transmitter is off the receiver can then discern the echo. This technique is not always advantageous. Since the echo cannot be recognized by the receiver while the transmitter is on, this system has a limiting minimum distance under which no determination of range may be made. This minimum-range is determined by the time duration of the pulse. A radio wave travels approximately 1 foot per nanosecond (10^{-9} seconds). This means that if

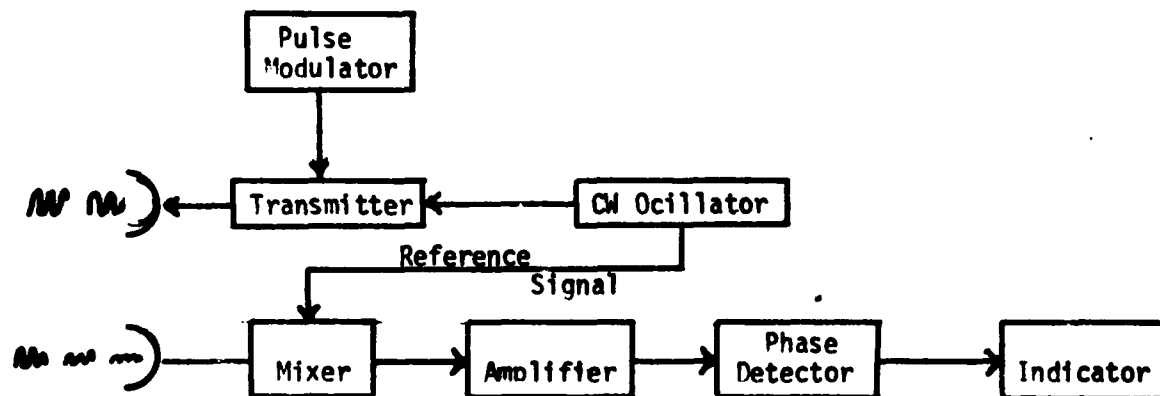
the pulse is one microsecond (10^{-6} seconds) in duration, the leading edge of the radio wave has traveled approximately 1000 feet before the transmitter cuts off. If a target is less than one half of this distance, i.e., less than 500 feet from the radar, the echo will arrive at the receiver before the transmitter has cut off and will not be sensed by the receiver. Equipment designed to shorten the pulse to very small durations is much more complicated and the problem becomes a trade-off between design problems, requirements, and costs.

Another disadvantage of this system is that the maximum range of the system is also limited not only by power output of the system but by the duration of time between pulses. The shorter the duration between pulses the smaller the maximum range. For example, if a pulse is transmitted and is reflected by a target the echo must be received before the next pulse is transmitted or there will be no way to distinguish which pulse was reflected, thereby introducing ambiguity.

Another disadvantage of this system is that fixed or stationary targets within a range which reflects a signal of equal or greater amplitude to that of a moving target cannot be distinguished by the radar.

PULSE DOPPLER RADAR

This radar system is capable of distinguishing between moving and stationary targets unlike the simple short pulse radar. A pulse radar which makes the use of the doppler information is known as MTI radar (moving target indication). This system like the CW radar makes use of a reference (usually a portion of the transmitted signal) and a mixer in order to detect the doppler frequency as shown in the figure below



If the CW oscillator operating voltage is represented as $A_1 \sin \pi f_t t$, where A_1 is the amplitude and f_t the carrier frequency, the reference signal is given by $V_{ref} = A_2 \sin 2\pi f_t t$, and the doppler-shifted echo-signal voltage is

$$V_{echo} = A_3 \sin \left[2\pi (f_t \pm f_d) t - \frac{4\pi f_t R_0}{c} \right]$$

where A_2 = amplitude of reference signal

A_3 = amplitude of signal received from target at range R_0

f_d = doppler frequency shift

t = time

c = velocity of propagation

Once both the reference signal and the echo signal are heterodyned in a mixer, the voltage difference due to the beat frequency produced by the mixer is given by the formula

$$V_{diff} = A_4 \sin \left[2\pi f_d t - \frac{4\pi f_t R_0}{c} \right]$$

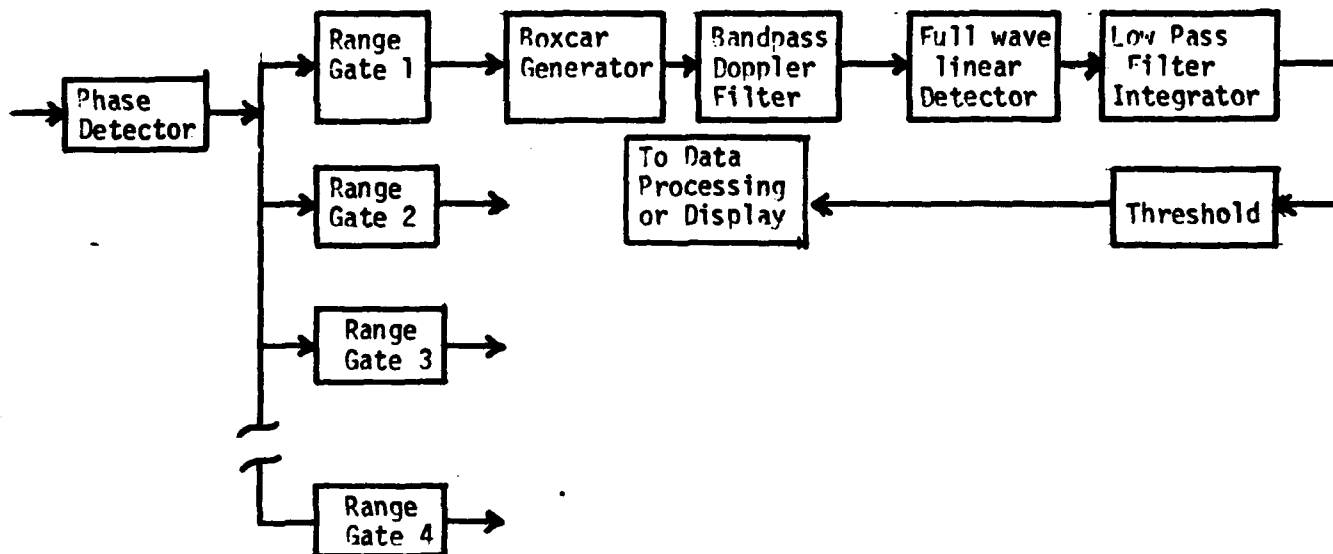
where A_4 is the amplitude of the voltage difference. From this equation and the measured voltage difference the range can be computed.

This system has the same disadvantages as the simple pulse radar; i.e., pulse duration limits the minimum range, and duration between pulses limits the maximum range. This system is, however, much more reliable in distinguishing moving targets from stationary ones.

RANGE GATING

In a pulse doppler system a delay-line circuit is used to filter out the clutter or noise due to the echoes from stationary objects. This circuit also filters some of the doppler frequency, however, and makes range resolution difficult. The loss of the range information may be eliminated by first quantizing the range (time) into small intervals. This process is called range gating. (Fig 1, 2, 3, Annex H) The width of the gate depends on the desired accuracy. It is usually

on the order of the pulse width. Range resolution is established by gating. Once the radar return has been quantized into range intervals, the output from each gate may be applied to a narrow-band filter since the pulse shape need no longer be preserved for range resolution as shown in the block diagram below



The output of the phase detector is sampled sequentially by the range gates. Each range gate opens in sequence just long enough to sample the voltage resulting from the waveform corresponding to a different range interval. The range gate acts as a switch or a gate which is opened or closed at the proper time. The range gates are activated once every pulse repetition interval. The output for a stationary target is a series of pulses of constant amplitude. An echo from a moving target produces a series of pulses which vary in amplitude according to the doppler frequency. The noise and clutter are then filtered and the filter output is sent through a threshold. This threshold is also a guard against noise and clutter. The threshold signal can then be sent to a data processor for range print out.

USEFULNESS TO USAIB

By referring to the criteria for an antitank MDI system and comparing each radar system against these criteria, it can be shown that the pulse doppler system is the most feasible system.

The simple CW radar can be eliminated immediately since it does not give any range determination. Without a range determination the radar system could only act as a round count device.

The FM-CW radar can also be eliminated. Although the system is designed to measure range, moving targets introduce an error in the range measurement due to the doppler shift. Modifications could be made to limit this error but the design complications outweigh the advantage gained.

The simple short pulse radar can also be eliminated since it cannot easily distinguish between moving and stationary targets. Modification to this system could limit this problem but the range resolution of the system could not practically meet the accuracy criteria of an MDI system.

The short pulse doppler system is designed to detect moving targets without interference from echoes caused by stationary objects. It is also designed to measure range to the target. The range-gated system seems to be more applicable than a simple pulse doppler because of range information distortion due to noise and clutter filtering in the simple system. The state of the art is such that a range-gated system can be practically produced to meet the criteria for an antitank MDI system.

LOGICAL APPROACH

By a process of elimination it has been shown that the range-gated pulse doppler radar system is most closely suited for an anti-tank MDI system. This system, however, does not provide x and y coordinates, which is one major criterion for the system. This can be accomplished and solutions are discussed in Annex I.

APPENDIX 1 TO ANNEX H

There are several radar systems presently being employed as miss distance indicators. Their relative worth has been demonstrated on numerous occasions and miss distance scoring is becoming more and more dependent on radar.

One of the simplest systems used is a single pulse doppler radar. The sensor, mounted in the target, uses step-keyed rf radiation to create an electro-magnetic sphere of influence around the sensor antenna. This is nothing more than a round count scoring system. As a round enters the sphere it is counted as a hit and transmitted to the recording station. Another system using the same basic instrumentation also makes use of range gating which provides a scalar distance the round passes from the antenna providing it passes through the sphere of influence. The size and shape of the sphere can be varied according to the type of sensor used. (Figure 4, Annex H)

Work is being done at present using two or more pulse doppler radars associated with a single target. An integrated target control system is being developed for use in the high altitude supersonic target for missile scoring. Similar systems have already been tested with moderate success. The basic principle involves three time synchronized pulse doppler radars which provide three scalar distances. Where these lines intersect at some point in space x, y, and z coordinates are provided. In the case of this study the target is two dimensional and would require only two radar systems for x and y coordinates. The disadvantages of the system are the dead spaces created around the sensor antennas and the requirement for proper positioning to permit maximum overlap of antenna patterns. These problems are being researched presently and are expected to be overcome in the near future. (Figure 5, Annex H)

Another type of radar - the MDI system - is a tracking radar which establishes slave gates short of and beyond the target. The slave gates are maintained at fixed distances from the main range gate which is in the target plane. As a projectile passes through the slave gates, azimuth and elevation offset of the projectile with respect to radar beam center are indicated. By knowing gate distance from the radar angular offset can be converted to linear offset normal to the line of sight. With a known displacement of the gate from the center of target, vector displacements of the projectile and target can be calculated. The major disadvantage of this system is cost.

There are other radar systems being used in addition to those mentioned above, but the point has been demonstrated that radar MDI systems are prolific at scoring and may be the best approach available today.

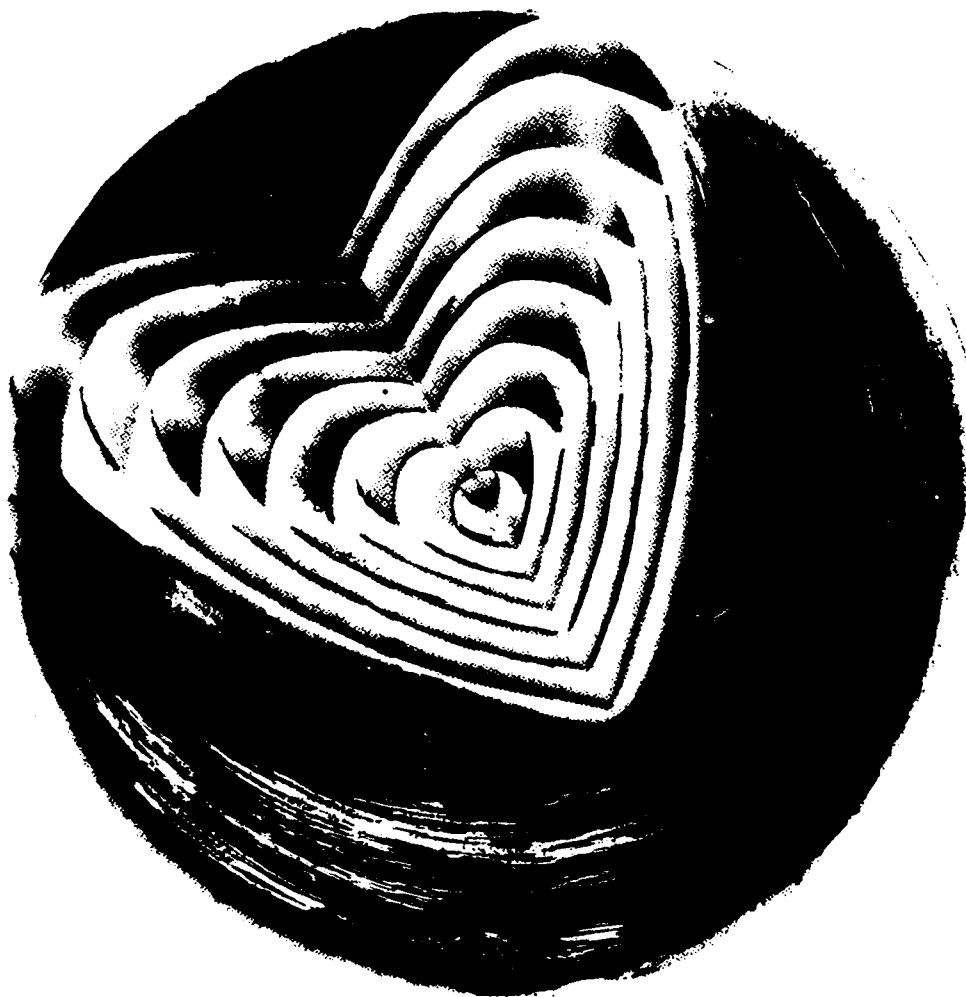


Figure 1, Annex H
SAMPLE ANTENNA PATTERN, RANGE - GATED RADAR

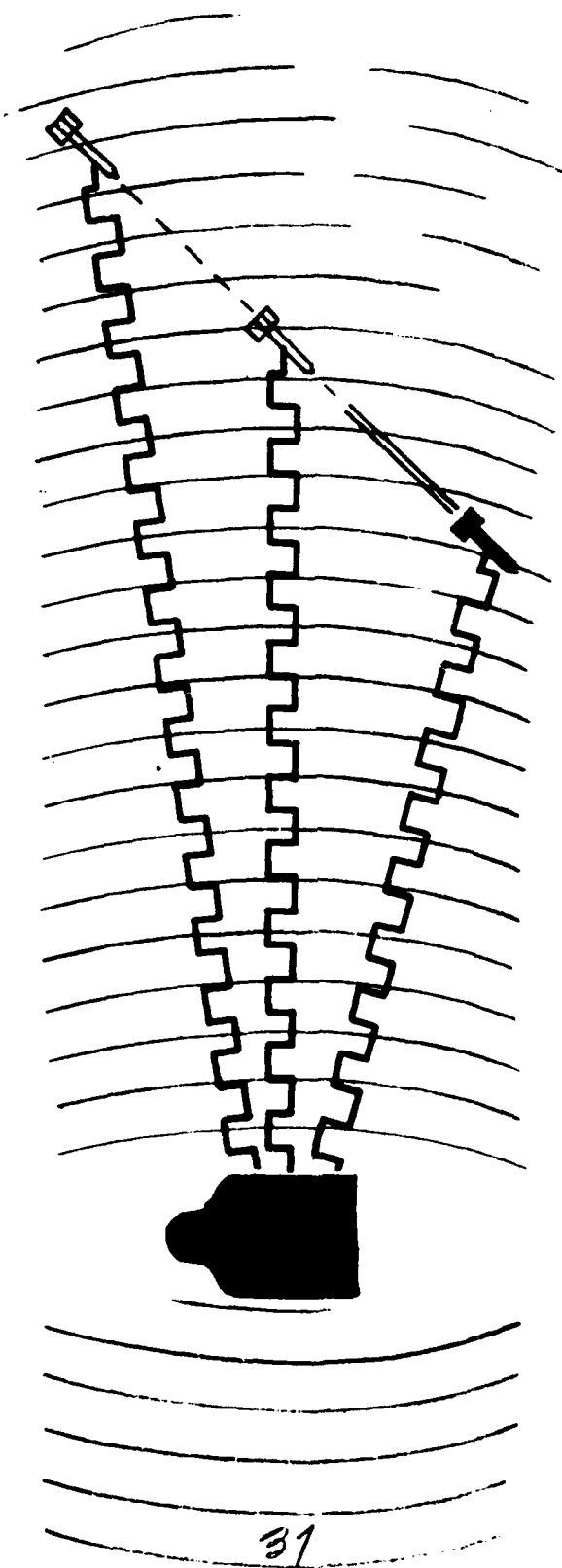


Figure 2, Annex H
RANGE - GATED SCORING

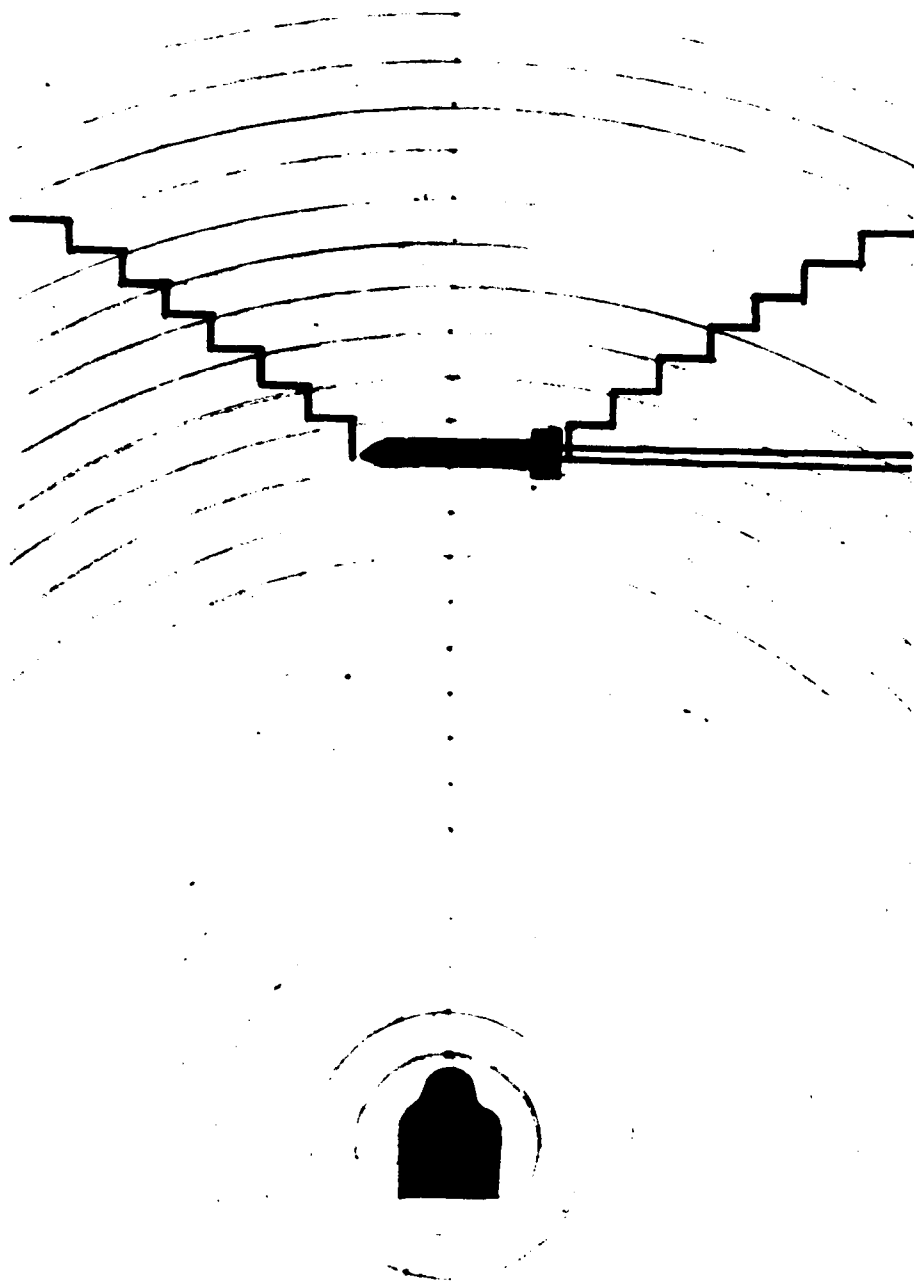


Figure 3, Annex H
RANGE - GATED SCORING

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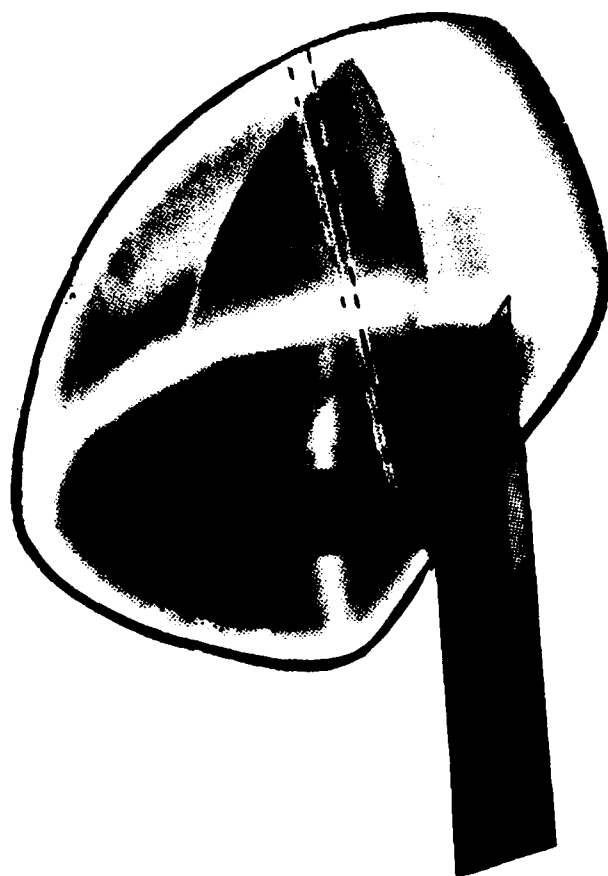


Figure 4, Annex H
RADAR ROUND COUNT SCORING SYSTEM

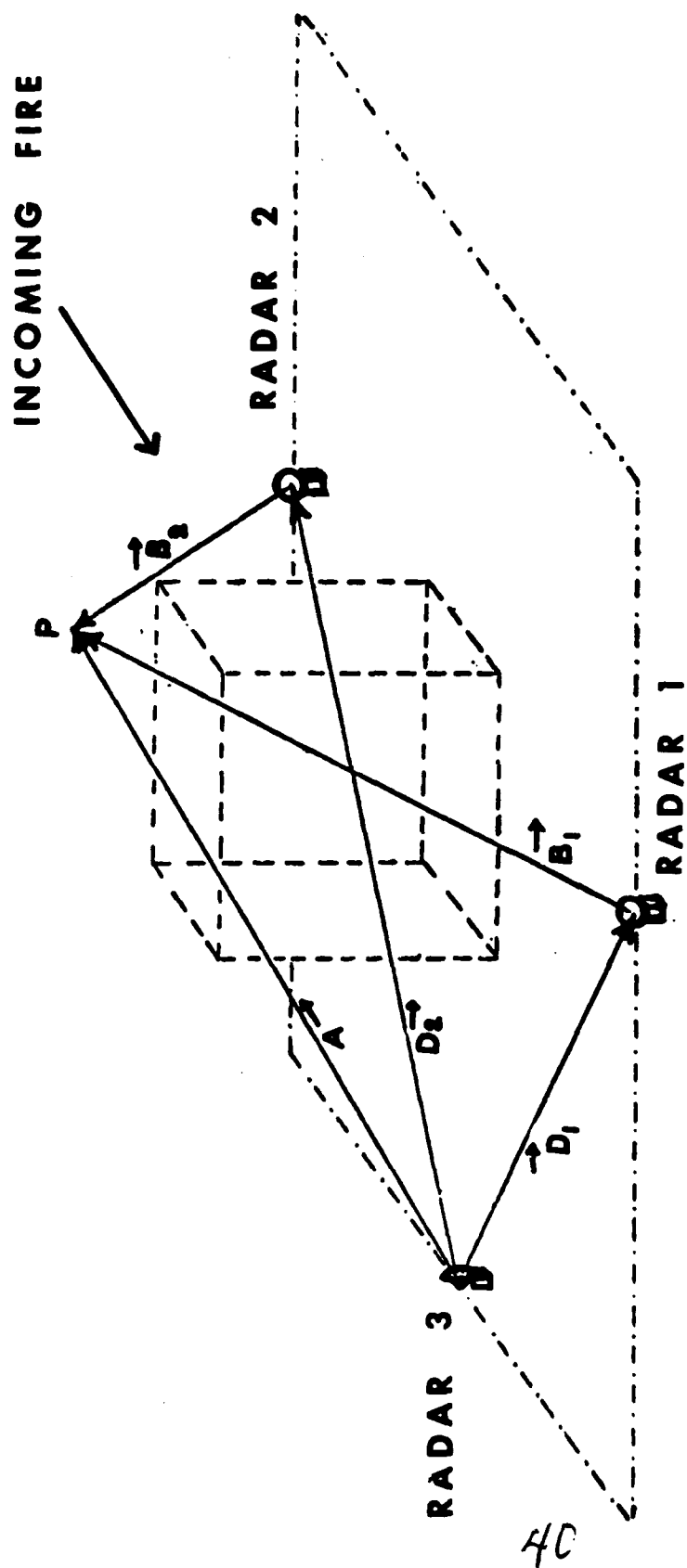


Figure 5, Annex H
RANGE ONLY RADAR MATRIX

ANNEX I

From the study of the state of the art of MDI systems it was determined that a system which provided real time readout of the x and y coordinates of a projectile as it passed through the target plane could meet the criteria. At present, however, there is no system configured to meet our specific criteria. A further study was conducted to determine the feasibility of such a system.

The first concept dealt with two radar antennas with overlapping coverage. Both antennas would send out a pulsing signal thus setting up a grid of interference patterns. By determining a particular interference pattern the x and y coordinates could easily be determined. This idea was quickly rejected because as the pulses from each antenna are propagated outward so would the interference pattern. Therefore, the grid of interference patterns would not be fixed in space and made determining one particular pattern's location at a particular instant in time impractical.

The second proposed solution is the most feasible and is still under study at this time. This proposed system consists of two antennas each sending out a pulsing signal of different frequencies. (See figure 2, Appendix 1 to Annex I). Using the doppler principle, as a projectile passes through the radar zone its distance from each radar antenna can be determined. Knowing the location of the antennas and the distance between them makes it a simple matter of triangulation to determine the x and y coordinates of the projectile. (See Appendix 1). Several factors will have to be considered.

1. Accurately determining the distance to the round using the doppler principle may present some difficulties although certain manufacturers do not foresee this as a problem. Considering that the maximum range we will be dealing with is about 30 feet and the fact that microwaves travel approximately 1 foot per nanosecond (10^{-9} seconds), a measurement of distance depends on the ability to measure time accurately.

2. Antennas would have to be very frequency selective so that emanations from one antenna would not cause interference at the other. This also presents the problem of picking up the doppler shift, i.e., if the antennas are so frequency selective it is possible that it may not pick up a change in frequency. This problem could be eliminated by operating the radar systems at the same frequency and synchronizing the two systems so that

one transmits while the other is off.

3. The time length of the radar pulse determines the distance the target must be from the antennas and this could become a limiting factor.

4. As the angle of entry of the projectile with target increases distance error increases, but manufacturers feel that there is a technique for overcoming this.

APPENDIX I

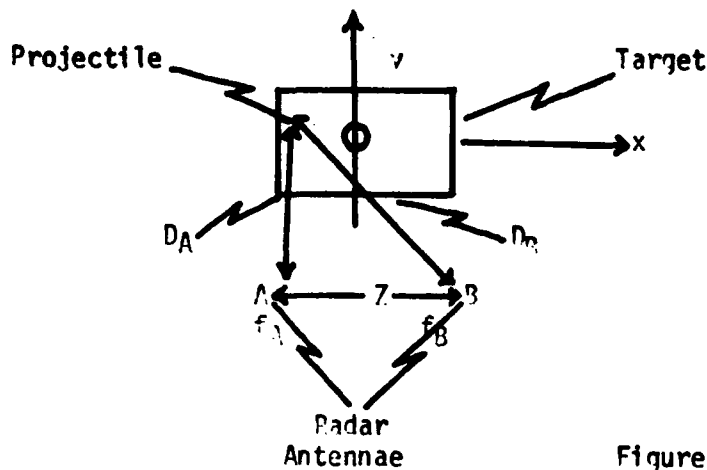


Figure 1

A - Radar Antenna A

B - Radar Antenna B

f_A - Radar Frequency Emitted by A

f_B - Radar Frequency Emitted by B

D_A - Distance from A to Projectile as Projectile passes Through Scoring Zone.

D_B - Distance from B to Projectile as Projectile Passes Through Scoring Zone.

$\Delta f_A'$ - Observed Frequency Reflected from Projectile at A.

$\Delta f_B'$ - Observed Frequency Reflected from Projectile at B.

v_a - Radial Component of Projectile Velocity with Respect to A.

v_b - Radial Component of Projectile Velocity with Respect to B.

c - Propagation Velocity of Microwave (Speed of Light)

f_A - Doppler Shift Frequency Observed at A.

f_B - Doppler Shift Frequency Observed at B.

$f()$ - function of

Z - Known Distance Between Radar Antennas.

The observed frequency reflected from projectile at A (f'_A) can be determined mathematically as shown below.

$$f'_A = f_A \left(\frac{c + v_a}{c - v_a} \right)$$

The doppler shift frequency or change in frequency observed at A is given by the formula below

$$\Delta f_A = f_A \left(\frac{c + v_a}{c - v_a} \right) - f_A$$

$$\Delta f_A = f_A \left[\left(\frac{c + v_a}{c - v_a} \right) - 1 \right]$$

$$\Delta f_A = f_A \left[\left(\frac{c + v_a}{c - v_a} \right) - \left(\frac{c - v_a}{c - v_a} \right) \right] = f_A \left[\frac{(c + v_a) - (c - v_a)}{c - v_a} \right]$$

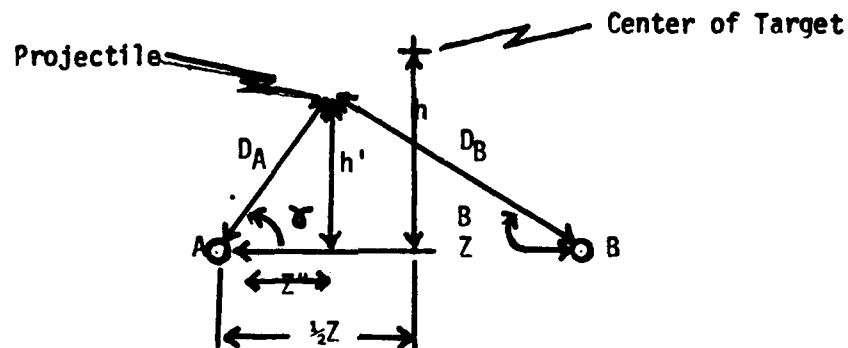
$$\Delta f_A = f_A \left(\frac{2 v_a}{c - v_a} \right)$$

Similarly

$$\Delta f_B = f_B \left(\frac{2 v_b}{c - v_b} \right)$$

Now assuming that the radar sets are in the plane of the target and the angle of incidence of the projectile with respect to the target is 90° , we see that there is no radial component of velocity with respect to either antenna at the instant the projectile passes through the target plane. Therefore both f_A and f_B are zero. If this change in frequency is measured, and when this change equals zero, an electronic timer is started to time the next pulse from each radar until its reflection is received the distance from each antenna to the projectile can be determined.

Knowing the distance from each antenna to the projectile the x and y coordinates may be easily computed. (See diagram and computation below).



h - Vertical Distance from Radar Antennas to Center of Target

h' - Vertical Distance from Radar Antennas to Projectile

z' - Horizontal Distance from A to Projectile

Now by definition

$$s = 1/2 (Z + D_A + D_B)$$

Knowing s the angle θ may be computed using:

$$\sin 1/2 \theta = \sqrt{(s - D_A)(s - Z) / D_A Z}$$

After determining the angle θ , Z' may be found and thus the X coordinate may be found as shown below.

$$Z' = \cos \theta D_A$$

$$X = Z' - 1/2 Z$$

Similarly h' may be determined and the y coordinate calculated.

$$h' = \sin \gamma D_A$$

$$y = h' - h$$

ANNEX J

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